

Soil Salinity Assessment by Some Destructive and Non Destructive Methods in Calcareous Soils

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Abstract

Salinity is a major problem limiting plant growth throughout the world. Various methods have been used to measure soil salinity. The destructive (standard) method involves soil sampling followed by laboratory measurement of electrical conductivity (EC) in saturated paste extracts, 1 : 1, and 1 : 5 soil and water suspensions. Whereas, a non destructive (Sigma probe) method give a direct measurement of soil pore water salinity. Various methods for measuring salinity are commonly correlated in similar soils. The objective of this study was to determine the relationships between salinity readings obtained from standard methods and Sigma probe in calcareous soils of different texture and salinity. Results from the laboratory methods (saturated paste extracts, 1 : 1, and 1 : 5 soil/water ratios) were generally highly correlated ($R^2=0.98$). Moreover, present of many salts in the soil were affecting linearity of the relationship between saturated paste extracts and 1 : 5 ratio in which the best correlation was found when the EC of saturated paste extract was less than 20 dS m^{-1} . Sigma probe was successfully correlated with standard methods. Its readings were relatively affected by soil salts and water content, in which the best correlation was found between Sigma probe reading and EC measured at saturated paste extracts values, at low water content with EC less than 10 dS m^{-1} . Many salts (ex. Na^+ , Ca^{2+} , Mg^{2+} ...etc.) were interfering the correlation equations between methods and as soil water increased more salts were dissolved and gave weak correlation factor (R^2). Using Sigma probe removes the need for soil sampling prior to salinity measurements and should allow *in situ* soil salinity measurements to be taken that could be related to standard methods. Moreover, readings of Sigma probe at low water content, which is around field capacity considered as the best measuring conditions. However, more researches with gradient increase in soil salinity and water content need to be done. Finally, soil properties and measuring conditions should be considered before applying any published method or equation for soil and water salinity evaluation. However, if the equations found in this study are suitable for certain soils, salinity measurements could be done in short time by Sigma probe and related to the standard methods.

Key words : Electrical conductivity, Sigma probe, saturated paste extract, soil/solution ratios

1. Introduction

Plant response is more related to the salt concentration of the soil solution than to the total salt content of the soil, on a weight basis

(U.S. Salinity Laboratory Staff, 1954). Soil salinity can be assessed from the electrical conductivity (EC) measurements of soil water suspensions representative of the soil solution. Methods are based on the principle that the

amount of electrical current transmitted by a salt solution under standardized conditions will increase as the salt concentration of the solution is increased (Rowell, 1994).

Salinity of the soil solution can also be estimated from the EC obtained from water extract of the soil. In general, the higher the water content, the easier it will be to obtain the extract, but the less representative the extracted solution will be the solution to which plant roots are exposed in the soil. Conductivity of the saturation extract is recommended as a general method for appraising soil salinity in relation to plant growth. The advantage of this method is that the saturation percentage is directly related to the field water content range. In addition, it is an easy and accurate method. Salinity estimates based on conductivity of 1 : 1 and 1 : 5 extracts are convenient for rapid determinations, particularly if the amount of soil sample is limited, or when repeated samplings is to be made in the same soil (Page *et al.*, 1982). Methods of saturation extract and soil/water ratios are destructive, money and time consuming especially if a large area should be sampled. Thus, there is a great demand for a new method.

Many sensors (ex. EC probe, four electrode, Sigma probe and TDR) were invented for easy and *in situ* measurements of soil salinity. The latest invention was time domain reflectometer (TDR) meter. It is a famous method for water content and salinity determinations based on detecting reflected signals as a function of time. This method required long time for calibrations and the initial costs are relatively high compared to other methods (Hamed *et al.*, 2003). The other method that was used in this study is Sigma probe. It is a non-destructive method for a direct measurement of soil salinity. It is an easy method for measuring soil salinity based on measuring accurately the permittivity and conductivity of the bulk soil. It measures the soil pore water EC independently from soil water content and degree of contact between probe electrodes and the soil

(Hamed *et al.*, 2003 and Hilhorst, 2000). For mapping large areas, evaluating lands for agricultural purposes and monitoring changes in soil salinity over time, Sigma probe is faster and involves less labor than standard methods. It is a new device in the field of science and its advantages and limitations need to be evaluated and clarified to the other users. Doing this study could also help in evaluating the accuracy of Sigma probe when it was used in different soil water content in calcareous soils compared with other standard methods.

Standard methods are well-known and good indicators for soil salinity but their limitations directed researchers to look for other methods and search for correlations between them. The objective of this study was to determine relationships between methods for measuring soil salinity, specifically results from Sigma probe versus standard methods.

2. Materials and Methods

2.1 Sigma probe

Sigma probe (type EC1, Delta T Devices, Cambridge, U.K) is a portable device (weight \approx 500 g) measures pore water conductivity independently from both soil moisture content and the degree of contact between the probe and soil (Fig. 1). The measurement is made possible by use of an integrated circuit to measure accurately the permittivity and conductivity of the bulk soil. This circuit is running inside Sigma probe and producing a continuous electrical field (voltage) around the sensor with frequency of 30 MHz (input signals). The ions (salts) around the electrical field will carry the energy (polarization) and the energy lost will be considered as the ions concentrations in the pore water (i.e. reduction in the output signals will be converted to salinity unit, dS m^{-1}). The conductivity of the pore water (σ_p) is calculated using the following equation :

$$\sigma_p = (\varepsilon_p * \sigma_b) / (\varepsilon_b - \varepsilon_0) \quad (1)$$

Where ε_p = Permittivity of pore water ; σ_b = Conductivity of bulk soil ; ε_b = Permittivity of

bulk soil ; and ϵ_0 =Permittivity of dry soil materials.

Sigma probe program eliminates the need for soil specific calibration and makes the readings insensitive to the degree of contact between probe and soil. The probe tip is specially designed both for ease of insertion into the soil and to enable local measurements of permittivity and conductivity. It is the combination of these features, which enables the pore water conductivity to be calculated reliably from the dielectric readings. The software provided with Sigma probe processes the dielectric data from the probe, calculates and displays the pore water conductivity and temperature. Readings usually stored electronically in a Psion Workabout sheet (Fig. 1). This sheet contains readings of EC, temperature, date, time, sample number, file name and note space. Measurements usually performed by turning on the device, write the date, time and file name. Inserting the probe in the soil and press enter for EC measurement. The device takes 10 seconds to read and store one reading (User

manual for Sigma probe, 2000, Hamed *et al.*, 2003 and Hilhorst, 2000).

This sensor was updated to W.E.T. sensor that working under same principles but it can measure soil water content in addition to the soil salinity and temperature (WET sensor, 2004).

2.2 Soil sampling and preparations

Thirty soil samples from surface (0–10 cm) and subsurface (10–20 cm) were obtained from 15 cultivated lands of Oman (22° 30' N 53° 30' E). Soils were selected from agricultural areas (ex. date palm, alfalfa, barley, tomato, ...etc) that had a wide range of salinity and textures. All samples were air dried at 25°C and passed through a 2-mm sieve (Tan, 1995). All soil samples were analyzed following chart in Fig. 2. Soil initial conditions (pH, cation exchange capacity, calcium carbonate, gypsum and clay percentage) were measured by following soil analysis methods (Tan, 1995 and Page *et al.*, 1982). Moreover, the end results were presented in Table 1.

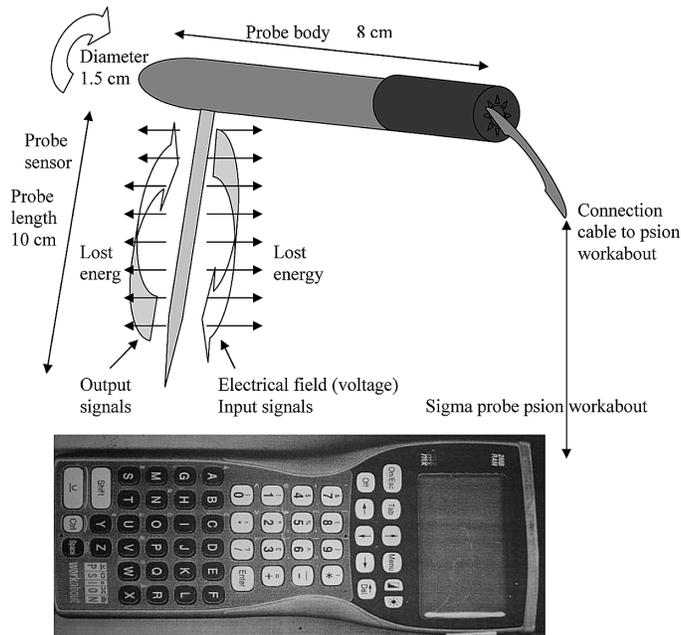


Fig. 1 Sigma probe (type EC1, Delta T Devices, Cambridge, U.K).

2.3 Soil salinity determination

For each soil sample, salinity was determined from electrical conductivity (EC) measurements in soil/water suspensions at three soil : water ratios, and measurements of soil pore water using a Sigma probe. Electrical conductivity (EC) of soil/water suspensions was measured by using distilled water in soil saturated paste extract, 1 : 1, and 1 : 5 ratios. After mixing, soil saturated pastes were left to stand for over night (20°C) before filtration under vacuum. Soil/water suspensions were shaken automatically for 1 hour and then filtered through 0.11 mm Whatman filter paper (Page *et al.*, 1982). EC extracts (EC_(sat.paste)) and suspensions (EC_(1:1, 1:5)) were measured by using a calibrated conductivity meter (Jenway, Conductivity Meter 4020, UK) connected to an EC electrode. Soil pore water salinity was measured using Sigma probe. It was inserted into either saturated soils, soils at 25% or 15% water content (volume/mass basis) prepared by mixing soil and water (bulk density = 1.2 g cm⁻³) to reach required percentage. In the paper, these water contents are referred to high, medium and low, respectively. EC read-

ings by Sigma probe were stored electronically and the average of three readings per sample was taken.

Soluble ions (Na⁺, Ca²⁺ and Mg²⁺) and soil adsorption ratio (SAR) were measured in saturated paste extract by using PYE UNICAM SP 9 Atomic Absorption Spectrophotometer (Tan, 1995 and Page *et al.*, 1982).

Results of soil salinity from different methods of assessment were compared by regression analysis, using statistical software (Statistical Package for Social Science, version 6, Coakes and Lyndall, 1997).

3. Results and Discussion

3.1 Standard methods

Table 1 details the properties of the soil studied. It includes estimates of soil parameters that interfere with soil salinity measurements. The collection of soils exhibited a range of physical and chemical properties, and the range of salinities covered that are found in agriculturally cultivated soils. Moreover, water holding capacity of the studied soils were estimated by the study done by Israelsen and Hansen (1962) in which he estimated field capacity (FC)

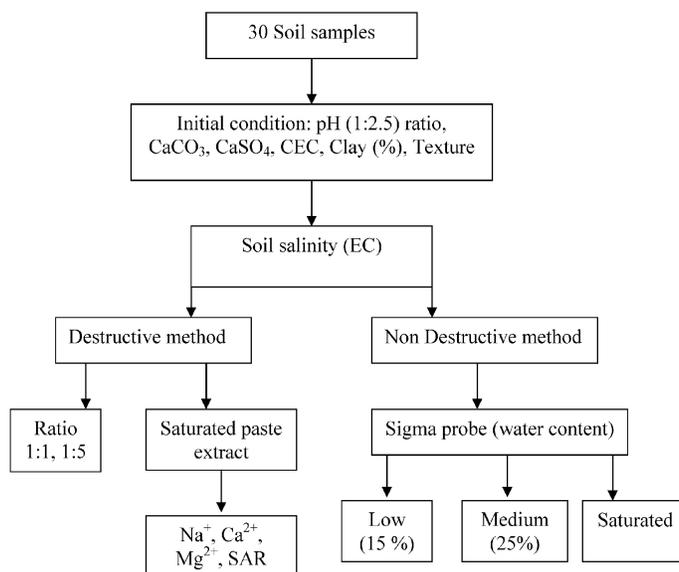


Fig. 2 General flowchart of soil analysis.

Table 1 Physical and chemical properties of the soil

Soil No.	Sampling depth (cm)	Soil properties							
		EC _(1:1) (dS m ⁻¹)	EC _(1:5) (dS m ⁻¹)	EC _(sat.paste) (dS m ⁻¹)	EC _(st) at Low WC (dS m ⁻¹)	SAR	Na (mmol ₍₊₎ L ⁻¹)	Ca (mmol ₍₊₎ L ⁻¹)	Mg (mmol ₍₊₎ L ⁻¹)
A1	0-10	0.29	0.15	0.67	1.12	2.66	5.44	6.25	2.08
A2	10-20	0.71	0.25	1.52	1.71	4.76	10.9	6.25	4.17
B1	0-10	0.34	0.16	0.77	0.98	4.21	5.44	1.25	2.08
B2	10-20	0.48	0.20	0.90	1.28	2.66	5.44	6.25	2.08
C1	0-10	1.09	0.36	1.78	2.12	5.33	10.9	6.25	2.08
C2	10-20	0.97	0.33	1.51	1.9	5.33	10.9	6.25	2.08
D1	0-10	1.30	0.37	4.25	3.17	8.42	27.2	12.5	8.33
D2	10-20	0.75	0.25	1.88	1.96	7.99	16.3	6.25	2.08
E1	0-10	1.02	0.35	1.82	1.91	7.99	16.3	6.25	2.08
E2	10-20	1.20	0.34	2.74	2.51	9.53	21.7	6.25	4.17
F1	0-10	17.4	3.99	31.4	—	15.0	130.4	68.8	83.3
F2	10-20	1.21	0.39	1.63	2.11	7.99	16.3	6.25	2.08
G1	0-10	2.15	0.59	3.7	3.10	8.05	21.7	6.25	8.33
G2	10-20	2.30	0.61	4.01	2.96	14.3	32.6	6.25	4.17
H1	0-10	4.51	1.07	12.6	10.3	17.6	76.1	12.5	25.0
H2	10-20	2.05	0.50	6.09	4.01	8.54	32.6	12.5	16.7
I1	0-10	7.27	1.33	11.2	6.32	15.8	87.0	31.3	29.7
I2	10-20	3.07	0.76	5.27	3.61	10.8	38.0	12.5	12.5
G1	0-10	8.46	1.88	17.3	13.2	23.7	130.4	18.8	41.7
G2	10-20	3.06	0.73	6.55	4.53	17.8	54.4	12.5	12.5
K1	0-10	5.27	1.19	13.6	9.31	14.6	87.0	25.0	45.8
K2	10-20	3.08	0.74	7.76	5.57	13.8	54.4	12.5	18.8
L1	0-10	19.5	4.43	53.4	—	32.5	347.8	62.5	166.7
L2	10-20	7.69	1.76	23.8	13.0	7.31	76.1	50.0	166.7
M1	0-10	8.51	1.96	20.7	19.4	23.7	141.3	25.0	45.8
M2	10-20	14.1	3.10	31.6	—	21.5	173.9	56.3	75.0
N1	0-10	15.6	3.38	39.1	—	19.8	217.4	75.0	166.7
N2	10-20	24.8	6.14	59.6	—	41.6	347.8	56.3	83.3
O1	0-10	25.9	7.46	69.7	—	30.1	347.8	100.0	166.7
O2	10-20	34.8	9.42	86.8	—	52.1	565.2	68.8	166.7

and permanent wilting point (PWP) of each soil depending on soil texture of the soil. Generally the studied soils were calcareous, alkaline and mostly light in texture. Present of all this variations in soils properties can give good reflections for different possibilities, interactions and finally more reliable equations and conclusions for different soils, in which the concluded equation can be generalized and applied to many different soils.

Table 2 presents linear regression equations

relating different standard methods of soil salinity determination, with R² values (i.e. the proportion of variance accounted for by the equation). For example, from the relationship between EC_(1:5) and EC_(sat.paste), it is necessary to multiply by 9.7 to convert EC_(1:5) to EC_(sat.paste) data. This finding was also clarified by Fig. 3, in which it can be seen that approximately a linear relationship was connecting those two different methods. It is shown that higher correlation was occurred when

Table 1 (Continue)

Soil No.	Soil properties							
	pH (1 : 2.5)	CaCO ₃ (g g ⁻¹)	CaSO ₄ (cmol _c kg ⁻¹)	CEC (cmol _c kg ⁻¹)	Clay (%)	^(a) Texture	^(b) FC (%)	^(c) PWP (%)
A1	9.02	0.34	<1.60	4.35	6.03	LS	10-18	4- 8
A2	8.71	0.49	<1.60	10.9	9.11	LS	10-18	4- 8
B1	9.25	0.60	<1.60	1.96	6.77	S	6-12	2- 6
B2	8.76	0.33	<1.60	8.70	16.3	SL	10-18	4- 8
C1	8.85	0.42	<1.60	10.9	21.7	L	18-26	8-12
C2	8.68	0.42	<1.60	16.3	24.9	L	18-26	8-12
D1	8.76	0.47	<1.60	2.17	4.02	LS	10-18	4- 8
D2	9.06	0.50	<1.60	2.17	10.2	LS	10-18	4- 8
E1	8.94	0.43	<1.60	10.9	17.8	SL	10-18	4- 8
E2	8.93	0.43	<1.60	4.35	10.0	SL	10-18	4- 8
F1	8.10	0.35	<1.60	10.9	30.0	CL	23-31	11-15
F2	8.86	0.41	<1.60	16.3	35.4	CL	23-31	11-15
G1	8.67	0.42	<1.60	16.3	19.4	L	18-26	8-12
G2	8.81	0.39	<1.60	21.7	19.9	L	18-26	8-12
H1	8.69	0.38	<1.60	2.39	5.13	S	6-12	2- 6
H2	8.79	0.58	<1.60	2.39	4.23	S	6-12	2- 6
I1	8.33	0.39	5.00	16.3	20.1	L	18-26	8-12
I2	8.40	0.42	<1.60	21.7	20.2	L	18-26	8-12
G1	8.31	0.42	<1.60	10.9	9.76	SL	10-18	4- 8
G2	8.96	0.47	<1.60	16.3	12.8	SL	10-18	4- 8
K1	8.33	0.44	<1.60	6.52	6.03	LS	10-18	4- 8
K2	8.40	0.49	<1.60	8.70	5.77	LS	10-18	4- 8
L1	8.23	0.42	<1.60	4.35	4.01	LS	10-18	4- 8
L2	8.07	0.28	<1.60	4.35	4.04	LS	10-18	4- 8
M1	8.33	0.46	<1.60	8.70	11.8	SL	10-18	4- 8
M2	8.22	0.36	<1.60	10.9	14.0	SL	10-18	4- 8
N1	8.19	0.42	1.60	6.52	9.85	SL	10-18	4- 8
N2	8.42	0.41	<1.60	6.52	11.7	SL	10-18	4- 8
O1	8.03	0.40	6.60	6.52	10.0	SL	10-18	4- 8
O2	8.30	0.35	10.0	8.70	15.9	SL	10-18	4- 8

^(a) Where L, S, LS, SL and CL are loam, sand, loamy sand, sandy loam and clay loam textures, respectively, ^(b) FC=Field Capacity with $\pm 2\%$, ^(c) PWP=Permanent Wilting Point with $\pm 1\%$.

EC_(sat.paste) values were less than 20 dS m⁻¹ and after that this relationship was affected by high values of soil salinity. Moreover, when the EC values were less than 10 dS m⁻¹, the relationship was much stronger and the regression line was approximately connecting all points of EC values (Fig. 3). Generally equations for this conversion have been developed by many researchers using other soils (Landon, 1984, Hernandez Bastida *et al.*, 2004, Rhoades *et*

al., 1989 and Elprince, 1985), and it was concluded that no one equation is suitable for all soil types. For other conversions other than saturated paste extract and 1 : 5 ratio were not highly studied by different researches because the most needed method for soil evaluation is saturated paste extract but the most easy way of getting the extract is by 1 : 5 ratio. In this study all methods were highly correlated (Table 2) with R² values of 0.98 and conversion

Table 2 Relationships between salinity standard methods

Method comparison	Relationship	R ²
EC(1 : 5), EC(sat. paste)	$EC_{(sat. paste)} = 9.70 * EC_{(1 : 5)}$	0.98
EC(1 : 1), EC(sat. paste)	$EC_{(sat. paste)} = 2.50 * EC_{(1 : 1)}$	0.98
EC(1 : 5), EC(1 : 1)	$EC_{(1 : 1)} = 3.80 * EC_{(1 : 5)}$	0.98

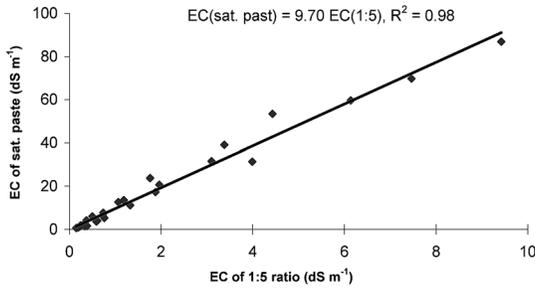


Fig. 3 Relationship between electrical conductivity (EC) measured by saturated paste extract and 1 : 5 ratio.

factors within acceptable level as compared with published equations.

Landon (1984) reported that the EC in saturated paste extract is higher by factors of 6.4 and 2.2 for $EC_{(1 : 5)}$ and $EC_{(1 : 1)}$ respectively. He established the following equations :

$$EC_{(sat. paste)} = 6.4 * EC_{(1 : 5)} \quad (2)$$

$$EC_{(sat. paste)} = 2.2 * EC_{(1 : 1)} \quad (3)$$

In other side, Elprince (1985) correlated $EC_{(1 : 3)}$ values with saturated paste and converted values to (1 : 5) basis, and found approximately same relationship as Landon (1984) but with lower values of R². The reported equation was as follows :

$$EC_{(sat. paste)} = 3.81 * EC_{(1 : 3)} \quad (R^2 = 0.77) \quad (4)$$

When $EC_{(1 : 5)}$ values exceed 6 dS m^{-1} , Elpince (1985) predicted that soil solutions would be over-saturated with respect to gypsum, and he concluded that this was the main reason for factor converting EC in the saturated paste extract to that in extracts of higher dilution to exceed the value 6.4.

Various causes for the differences in conver-

sion factors between soils have been suggested. One of the causes may be the presence of carbonates and gypsum in soil, especially when in high amounts. Differences in soil salinity can also cause deviations in the conversion factor. Hernandez Bastida *et al.* (2004) reported that the measurement of EC in saturation extract was a good saline content indicator only when the salt content was low but less suitable in the presence of high Cl^- or Na^+ concentrations. The behavior of the ions in the 1 : 1 soil solution extract was the same. Increasing of EC above 1 S m^{-1} result in a great dispersion of the points and a corresponding loss in linearity between the different parameters. The best correlation model between the EC value measured saturation and 1 : 1 extracts was a third order polynomial, although good results were obtained with linear and quadratic models (Hernandez Bastida *et al.*, 2004).

Any dilution above field conditions introduces errors in the interpretation of soil salinity data. The higher the dilution, the greater will be the deviation between ionic ratios in the sample and the soil solution under field conditions. These errors are associated with mineral dissolution, ion hydrolysis, and changes in exchangeable cation ratios. The ionic strength of soil solution in soils containing gypsum deviate more than other soils because the calcium and sulfate concentrations remain nearly constant with sample dilution, while the concentrations of other ions decrease with dilution (Tanji, 1990). As a consequence the uniformity of relationships between EC in extracts and the conditions of the soil solution for different soils is lost with increasing sample dilution. Rhoades *et al.* (1989) reported that the water

content of a saturate paste is about twice the field capacity for most soils. However, exceptions included sandy soils, organic soils, and soils containing gypsum. After taking into account these exceptions, the advantage of the saturated paste technique was that the procedure enabled the development of crop tolerance tables that could be interpreted across soil texture classes (U.S. Salinity Laboratory Staff, 1954). In general, there were no great variation in the behavior of the different ions between the 1 : 1 and soil saturation extract, except in case of Ca^{2+} , which showed the greatest propensity to form ionic pairs, which might influence EC because of the lower ionic activity of the elements in the extract (Hernandez Bastida *et al.*, 2004).

All reviewers in this finding are relating differences in EC equations are due to different association with mineral dissolution, ion hydrolysis, and changes in exchangeable cation ratios. Some of them are relating on NaCl, Ca^{2+} or gypsum in playing a main rule in these differences. Soil salinity usually has a strong relationship with many salts in the soil. From Fig. 4, it is clear that studied soils had a good relationship with Na^+ , Ca^{2+} and Mg^{2+} ($R^2 = 0.99$), so it is expected that any variations in their concentration will affect soil salinity and predicted equation. Soil Na^+ , which usually connected with Cl^- was participating by 75% in evaluating soil salinity measured by saturat-

ed paste extract methods and followed by Ca^{2+} and Mg^{2+} using standardized data by standard regression coefficient. This high percent of Na^+ can play one of the main rules in controlling soil salinity and different conversion factors. In addition, the studied soils are calcareous soils and present of calcium ions and other salts (Table 1) could be the major reasons for interfering differences in equations between different methods. From other side, more water added to each soil as a dilution factor (ex. from 1 : 1 to 1 : 5 ratio) could give more chance for other salts to be dissolved and affect some physical (surface area) or chemical (pH) reactions. Whereas having a common criterion between soils (calcareous) could help in directing EC reactions and giving good relationships between methods (Table 2).

3.2 Evaluation of Sigma probe

In the present study, the actual values of Sigma probe readings ($\text{EC}_{(\text{si})}$) at different soil water content and standard methods were correlated (Table 3). It can be seen that the highest correlation (R^2) among all equations was with Sigma probe readings at low water content and saturated paste extract. However all standers methods were giving the best correlation factors (0.85, 0.90, 0.91) with low water content of Sigma probe readings. It seems that medium and high water contents were not highly preferable because under these conditions more water will diffuse salts away from

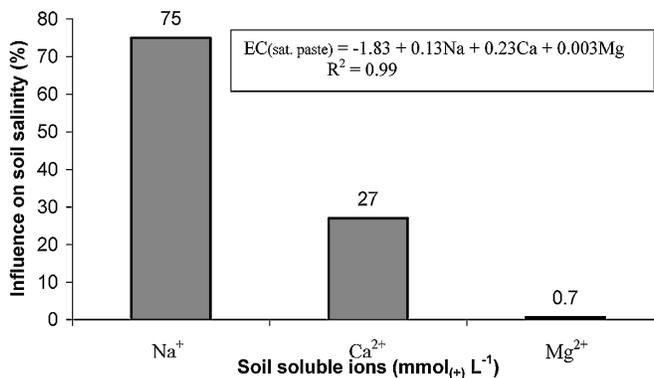


Fig. 4 Influence of soil soluble ions on soil salinity ($\text{EC}_{\text{sat. paste}}$) values.

Table 3 Relationships between salinity standard methods and Sigma probe readings

Method comparison	Relationship	R ²
S.I. (low WC), EC (sat. paste)	$EC_{(sat. paste)} = 1.30 * EC_{(si)}$	0.91
S.I. (low WC), EC (1 : 5)	$EC_{(1 : 5)} = 0.11 * EC_{(si)}$	0.90
S.I. (low WC), EC (1 : 1)	$EC_{1 : 1} = 0.52 * EC_{(si)}$	0.85
S.I. (medium WC), EC (sat. paste)	$EC_{(sat. paste)} = 1.47 * EC_{(si)}$	0.87
S.I. (medium WC), EC (1 : 5)	$EC_{(1 : 5)} = 0.12 * EC_{(si)}$	0.86
S.I. (medium WC), EC (1 : 1)	$EC_{(1 : 1)} = 0.57 * EC_{(si)}$	0.81
S.I. (high WC), EC (sat. paste)	$EC_{(sat. paste)} = 0.24 * EC_{(si)}$	0.41
S.I. (high WC), EC (1 : 5)	$EC_{(1 : 5)} = 0.02 * EC_{(si)}$	0.45
S.I. (high WC), EC (1 : 1)	$EC_{(1 : 1)} = 0.10 * EC_{(si)}$	0.40

WC is soil water content, where high, medium and low refer to saturated soils, 25% and 15% (v/m basis), respectively ; S.I. refers to Sigma probe.

the probe and give inaccurate readings. Whereas low water content is like a field capacity conditions which give more actual values and representing salts concentration in the soil solution extract. Sigma probe readings at low water content are around field capacity rang for most soils in Table 1 in which it can be recommended to use Sigma probe when the water content in the field is around field capacity.

Fig. 5 shows the best fitting line between measured values of Sigma probe and saturated paste extracts. Generally it isn't a linear relationship. It was started with linear relationship when soil salinity was low but as soil salinity getting higher many salts were interfering this relationship and the correlation line smoothly went down. However, the most reliable readings of Sigma probe were approximately up to 10 dS m⁻¹ of saturated paste extract and it was difficult for the probe to detect salinity when the salinity of saturated paste extract exceed 20 dS m⁻¹. In addition, the maximum value of the EC that can be measured by Sigma probe is up to 20 dS m⁻¹ (Table 1) and above that, it is difficult for the probe to detect soil salinity. This limitation was due to manufacturing design and calibration line, which is mainly controlled by the manufacturers. In addition, present of many salts could affect

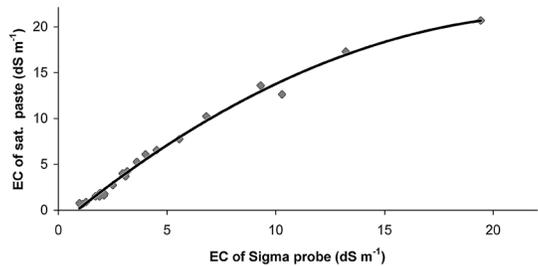


Fig. 5 Relationship between electrical conductivity (EC) measured by saturated past extract and Sigma probe at low water content.

calibration model and the reading will be out of designed range (0–20 dS m⁻¹).

For other concern of this study, the readings of Sigma probe were compared to the standard saturated paste extract (EC_(sat. paste)) method, with the aim of generating a set of calibration formulas to convert a reading from the probe to that of the recommended standard method. The latter method is time consuming and hence expensive to perform. Most calibration studies use pre-selected values of the independent variable (Scheffé, 1973). However, in this study, both independent and dependent variables are subject to error. The aim was to compare the methods and investigate their relationship under the conditions in which the probe will normally be used. But because of the accuracy with which the values of

$EC_{(sat.paste)}$ were measured, it is reasonable to assume that they have negligible variability. A logarithmic transformation of both pairs of data was found to achieve reasonably linear predictor-response relationships. The standard linear regression techniques were used to fit the transformed data, the results of which were then converted to the original units of measurement. Table 4 gives the calibration models finally adopted, together with the corresponding 95% confidence interval equations. All three equations with high (sat.), medium (25%) and low (15%) water content were found highly significant, and the coefficient of determinations (R^2) is 0.97, 0.96 and 0.99, respectively. The residual analysis of all three models indicated a good fit. Only the regression line of the readings for the low soil water content had a zero intercept. In addition, the coefficient of variations of all three values of the slope of the regression lines were less than 0.05, indicating that this particular parameter was accurately determined for each model. The confidence interval equations should therefore provide good approximations of the exact intervals. Equations in Table 4 can be applied to the field

conditions by justifying soil water content indicated by field capacity condition or water holding capacity of the soil. In this study, the best readings of Sigma probe were found to be at low water content (15%) in which it is near or around the range of the field capacity of most studied soils (Table 1).

Hamed *et al.* (2003) reported that Sigma probe gives fairly good results in the sandy soil but as the clay content increases, the correlation factor between Sigma probe readings and soil water salinity decreases, especially at low soil water salinity. In average, Sigma probe measured soil water salinity was within 20% of the correct value for all soil types when soil water salinity $> 1 \text{ dS m}^{-1}$. This study was also confirming this finding and that can be seen in equations between Sigma probe readings and soil texture (Table 5). It is clear that coarse texture, which contains clay particles $\leq 10\%$, give better correlation ($R^2=0.50$) than fine soils ($R^2=0.22$). Usually clay soils contain more elements than sandy soils in which they are affecting or deviating EC values. From Table 5, it can be seen also that $EC_{(si)}$ with low water content gave a good relationship ($R^2=0.97$)

Table 4 Calibration equations and the corresponding 95% confidence region equations of the probe readings for the three soil water contents

Soil water content	Equation	95% Confidence interval equations	(R^2)
High (sat.)	$\text{Ln } \hat{x} = -0.34 + 1.38 \text{ ln } y$	$\text{ln } \hat{x} \pm 0.39 \left[\frac{(\text{ln } y - 1.26)^2}{13.6} \right]^{1/2}$	0.97
Medium (25%)	$\text{Ln } \hat{x} = -0.32 + 1.45 \text{ ln } y$	$\text{ln } \hat{x} \pm 0.43 \left[\frac{(\text{ln } y - 1.191)^2}{13.6} \right]^{1/2}$	0.96
Low (15%)	$\hat{x} = y^{1.18}$	$(y^{1.12}, y^{1.24})$	0.99

Where \hat{x} and y are EC (saturated paste extract) and EC (Sigma probe) values, respectively.

Table 5 Influence of soil texture and ions on soil salinity measured by Sigma probe (low water content)

Soil factor	Relationship	R^2
Fine soils (Clay $> 10\%$)	$EC_{(si)} = -0.13 \text{ Clay } (\%) + 6.04$	0.22
Coarse soils (Clay $\leq 10\%$)	$EC_{(si)} = -1.38 \text{ Clay } (\%) + 14.23$	0.50
Ions	$EC_{(si)} = 1.12 + 0.12 \text{ Na}^+ - 0.20 \text{ Ca}^{2+} + 0.08 \text{ Mg}^{2+}$	0.97

with soil ions (Na^+ , Ca^{2+} and Mg^{2+}) which mean that Sigma probe is like any meter that can be affected by salt concentration in the soil.

To assess the appropriateness of each model, some values of $\text{EC}_{(\text{si})}$ were used to obtain the corresponding $\text{EC}_{(\text{sat. paste})}$ values by the formulas in Table 4. Table 6 shows the estimated values of $\text{EC}_{(\text{sat. paste})}$ together with their 95% confidence intervals. While lower readings of $\text{EC}_{(\text{si})}$ appeared to give good estimates of $\text{EC}_{(\text{sat. paste})}$, high values of $\text{EC}_{(\text{si})}$ gave unacceptably high estimates when high and medium soil water contents formulas were used. Judging by the confidence widths of the estimates, the power function obtained from the low soil water content readings gave the best results, while medium soil water based formula, having the widest confidence widths had the worst results. For instance, for $\text{EC}_{(\text{si})} = 10.0$, we get the estimate of $\text{EC}_{(\text{sat. paste})}$ as 17.0 (11.3, 25.6), 20.4 (12.9, 32.3) and 15.1 (13.1, 17.5) using the equations for high, medium and low soil water contents, respectively. It is clear that the confidence interval width is least for the last estimate, indication that it is also the best estimate of the three. Auerswald *et al.* (2001) found that electrical conductivity of the soil depend highly on water content, when it was low, EC

changed little but when water content was around field capacity the changes become larger. There is little difference among the three models for small values of $\text{EC}_{(\text{si})}$. To illustrate this we estimated $\text{EC}_{(\text{sat. paste})}$ for $\text{EC}_{(\text{si})} = 2.0$, and obtained 1.85 (1.24, 2.77), 1.99 (1.27, 3.10), and 2.26 (2.17, 2.37), respectively. The last model still had the smallest confidence interval width of 0.20 compared to 1.53 and 1.83 for the models from high and medium soil water contents, respectively.

The soil liquid and solid fractions both contribute to the total soil EC. The contribution of the solid fraction depends on the number of the exchangeable ions adsorbed to the surfaces of clay and organic matter (Nadler and Frenkel, 1980). This contribution tend to depend on the water content (Rhoades *et al.*, 1989) because a reduction in water content results in increased Coulomb interactions, due to attractions between free ions and the solid particles. Polarization, dispersion, and the arrangement of water molecules close to the clay surface (Cremers *et al.*, 1966) have influence on the EC of the solids. The combined effects of these interactions make the contribution of the solid fraction to EC complex (Amente *et al.*, 2000).

Bottraud and Rhoades (1985) reported that

Table 6 Applications of the calibration equations for selected values of Sigma probe readings (N=23 soils)

Sigma probe reading (dS m^{-1})	Soil water content	Estimate of $\text{EC}_{(\text{sat. paste})}$ value (dS m^{-1})	95% Confidence interval	Confidence width
2.0	High (sat.)	1.85	(1.24, 2.77)	1.53
	Medium (25%)	1.99	(1.27, 3.10)	1.83
	Low (15%)	2.26	(2.17, 2.37)	0.20
5.0	High (sat.)	6.55	(4.40, 9.75)	5.35
	Medium (25%)	7.48	(4.80, 11.7)	6.90
	Low (15%)	6.68	(6.04, 7.40)	1.36
10.0	High (sat.)	17.0	(11.3, 25.6)	14.3
	Medium (25%)	20.4	(12.9, 32.3)	19.4
	Low (15%)	15.1	(13.1, 17.5)	4.40
15.0	High (sat.)	29.7	(19.4, 45.4)	26.0
	Medium (25%)	36.7	(22.8, 58.9)	36.1
	Low (15%)	24.4	(20.6, 29.0)	8.40

volumetric water content, soil water EC, apparent EC of the solid phase and transmission coefficient have high relation to the soil EC. It is possible that some other expressions or parameters would be better than those described above, either in general or for specific situations and uses. In all cases, the prediction value for each calculation depends on prediction technique, calculation model and EC measurement methods (Rhoades *et al.*, 1990). Since this study tries to generalize a common idea or equation so generally all those opinions and expectation are applicable. Adding more water to the soil will help in dissolving more salt and complicating soil reaction, which leads finally to a weak correlation coefficient (R^2). While less water content keep the soil simple, easy to control and produce a good relationship between methods (Table 3). In addition to that interactions between measured values and choosing the appropriate model helped a lot in finalizing each equation (Tables 4 & 6). If this study was done in one kind of soil, the variations between parameters will be small and lead to better understanding of soil system, measured values and predicted equations, but the final findings can not be applied or generalized to different soils. In this study, different soils were used so different parameters were affected measured values and the expected or final equation could be applicable for many soils.

Hamed *et al.* (2003) concluded that Sigma probe was relatively in expensive, easy to handle and can be used for different soil types without calibration. Variations between soils, methods and meters can lead to different equations and models. If those variables can be specified, many parameters that interfering plant growth can be predicted. Each soil salinity method has its own limitation that can be solved by other methods. Sigma probe and standard methods are still in use until today and those equations that were predicted in this study can help in correlating many methods with each other. Sigma probe is an easy device

for pore water salinity measurements but it was seen that this device was relatively affected by soil water content. In addition, the accuracy of measured value was also affected by soil salinity in which the best range was found to be between $0-10 \text{ dSm}^{-1}$ of EC saturated paste extract and maximum values was up to 20 dSm^{-1} . Generally, each EC meter has its own advantages and limitations but soil is a complex system and deciding the right meter or equation for each soil or different soils need many efforts and researches. Finally, generalizing a certain equation in any field need many confirmations by many scientists and researchers and those information's found in this study could help in progressing science and be useful for many users.

4. Conclusion

The measurement of electrical conductivity in mixtures of soil and water is a convenient method for assessing soil salinity. However, diluting soils with increasing amounts of water not only reduces the electrical conductivity of the resulting suspensions but also changes the conversion factor required when soil salinity has been determined using different soil to water ratios. For calcareous soils from Oman, the relationships between $EC_{(\text{sat. paste})}$, $EC_{(1:1)}$ and $EC_{(1:5)}$ were statistically reliable, with R^2 values equal to 0.98. Moreover, the presence of soluble calcium and other salts in the soils, probably contributed to the high factors required for converting between $EC_{(\text{sat. paste})}$ and $EC_{(1:1)}$ or $EC_{(1:5)}$, i.e. 2.5 and 9.7 respectively, compared to the literature values of 2.2 and 6.4.

The use of Sigma probe to estimate soil pore water salinity was rapid, requiring only about 10 seconds from probe insertion into the soil to taking a reading. Results from Sigma probe were significantly linearly related to the other EC methods under study (soil saturated paste extract, 1 : 1, and 1 : 5 soil/water ratios), more closely associated when data were transformed to a power function. The use of power functions to relate Sigma probe readings to

EC_(sat. paste) values at soil water contents varying from 15% to saturation resulted in R² values exceeding 0.96. Sigma probe readings from soils low in water content had the highest correlation with EC_(sat. paste) values. The calibration equation obtained from these readings had the least confidence widths compared to the ones from either saturated soils or at moisture contents of 25%.

It is concluded that the most reliable readings of Sigma probe were obtained when the EC_(sat. paste) value was less than 10 dS m⁻¹, corresponding to low and moderate salinity. Sigma probe readings from increasingly saline soils provided progressively less reliable estimates of EC_(sat. paste) values. Moreover, Sigma probe readings gave the best correlations with other methods when soil water content was at lower value (15%), which is near or around field capacity condition. Further experiences with the probe need to be examined, especially with highly saline soils and gradual increment of soil water content to determine the yield response of different crops to salinity at prescribed soil pore water salinity, as measured using Sigma probe. Moreover, relationships between studied and published methods (destructive and non destructive) were highly dependent on soil properties and measuring conditions in which those specifications should be considered before applying any of those methods or correlated equations.

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いくつかの攪乱および不攪乱方法による石灰質土壌中の塩濃度測定

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要 旨

作物の生育を制限する塩類集積は、乾燥・半乾燥地域をはじめ世界中で問題になっている。土壌の塩類化の目安として、土壌抽出液の電気伝導度 (EC) を測定することが多く、これまでに様々な手法が用いられてきた。破壊的な方法として、土壌試料を採取した後、ペースト状の飽和抽出液、あるいは土壌試料と水との比が 1:1, 1:5 となるような懸濁抽出液を調製し、その EC を測定する方法があり、一般的な方法である。一方、非破壊的に測定する方法として、シグマプローブと呼ばれる土壌水の EC を直接測定する方法がある。本研究の目的は、土性および塩濃度の異なる石灰質土壌を用いて、土壌水抽出液の EC 測定とシグマプローブによる EC 測定との関連性を検討することである。

抽出液の EC 測定とシグマプローブによる EC 測定の結果は、全体的に高い相関 ($R^2=0.98$) を示した。さらに土壌中に多くの塩が存在するとき、ペースト状にして得られた飽和抽出液と 1:5 懸濁液の EC との間に直線的な相関が得られ、20 dS/m 以下の EC の場合、最も高い相関が得られた。シグマプローブによる測定値は、土壌水分量や土壌水中の塩類による影響を受けるが、飽和抽出液の EC 測定値と最も相関が高かったのは、土壌水分量が低く、10 dS/m 以下の EC の場合であった。土壌水中に様々な塩類 (例えば、 Na^+ , Ca^{2+} , Mg^{2+} など) が混在する場合や、より多くの塩類が溶解した場合に相関係数 (R^2) は低くなった。シグマプローブの使用により、土壌水の EC 測定のための土壌採取が不要となり、現場において、土壌水抽出後の EC 測定方法と遜色のない測定結果が得られるであろう。さらに、シグマプローブによる EC 測定は、圃場容水量程度の低い土壌水分量の場合が最適な測定条件と考えられる。しかしながら、土壌塩類や土壌水分が増加する場合に、さらなる研究が必要である。最後に、あらゆる確立された方法や式を土壌中の塩分量や水分量の推定に適用する前に、土壌特性や測定環境を考慮する必要がある。しかしながら、本研究で求めた方程式がある土壌で適合しているのならば、塩類の測定はシグマプローブによって短時間で行うことが可能であり、標準の方法における値と関連づけることができる。

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